Grantee: Cold Climate Heat Pump Demonstration
Project Name: Cold Climate Housing Research Center

Grant and Project#: 7310026 / 413005 / DC 01438

Grant Completion Report

Background: Increasingly ground source heat pumps (GSHPs) are being adopted as efficient heating devices for residential and commercial buildings in Alaska; however, questions about their long-term efficiency in severe cold climates remain. The study was designed to determine if long-term performance of a GSHP is stable in a severe cold climate and to thoroughly characterize its efficiency over multiple heating seasons by evaluating thermal degradation of the ground loop field. This is a fundamental challenge for adoption of the technology in cold climates. The study developed mathematical models and collected data from a demonstration heat pump system to determine and evaluate the long-term performance of a GSHP in a cold climate setting.

The Cold Climate Housing Research Center (CCHRC) tested and demonstrated the potential for GSHPs in cold climates to expand the range of efficient, clean space heating options for Alaskans. CCHRC installed the GSHP system at its Research and Testing Facility (RTF) located at the University of Alaska Fairbanks. The GSHP displaced an oil-fired boiler that heated the eastern half of the RTF, and provided space heating for approximately 5,000 square feet via low-temperature hydronic distribution.

Fairbanks has discontinuous permafrost, most of it is warm at 30 to 32°F. The ground around the RTF was found to be thawed to a depth of approximately 30 feet, which provided a narrow band for optimizing the bury depth of the ground loop between the zone of seasonal frost and the underlying permafrost. These were challenging conditions for the operation of a heat pump system and did provide a rigorous testing environment for using GSHPs in Alaska. Lessons learned during the design, installation, and maintenance of a GSHP at CCHRC provided valuable insight into the potential of GSHPs in Alaska and the optimal design for cold climates. Furthermore, testing this emerging technology at the RTF provided a controlled research setting and high-visibility environment, both of which are important in overcoming implementation barriers.

CCHRC also tested ways to mitigate thermal degradation in the soil by monitoring the effects of three ground surface treatments that are practical for homeowners or facility managers to implement. It sought to enhance ground heat collection during summer months and to minimize cooling during winter months. The surface treatment types included grass, dark gravel and sand. Each type encompassed approximately one-third of the area of the ground loops.

Activities: The principle activities conducted under this grant include the following: 1) thermal response test of site; 2) design of the heat pump system; 3) update of the monitoring plan; 4) installation of the ground loop system; 5) installation of the heat pump system; 6) installation of the data acquisition system; 7) commissioning; 8) system monitoring and maintenance for four heating seasons; 9) data analysis, life cycle assessment (LCA) and draft final report; and 10) final project report.

Work began on this grant in fall of 2012 with a soil thermal conductivity test conducted at the site designated for the installation of the ground loop. The test consisted of the installation of a temporary heat transfer loop at 9 feet depth with circulation of fluid and the addition of heat. Temperature measurements were made before and after the tests and soil samples taken to determine soil thermal characteristics and subsurface conditions. The initial temperature of the soil at 9 ft.depth was found to be 34 F. This information influenced the next activity, the design of the ground heat exchanger (GHE).

The system design took place in spring of 2013. Six 100 ft long by 3 ft wide slinky coils with an 18 in. pitch were installed 6 ft apart. Overall, the GHE consisted of 22,000 ft2 with 3 distinct heating sections with a total of 4,800 ft of 3/4 in. HDPE pipe at 9 ft depth. Other aspects of the system design were to specify the heat pump characteristics, thermal transfer fluid, transfer pumps, heat exchangers, etc. The heat pump was sized to heat the 5,000 ft2 office space on the east side of the building with a design heat load of 60,000 BTU/hr. The heat pump selected was a residential 21 kW (6 ton) water to water unit. It was connected to the existing in-floor hydronic heat delivery system of the RTF. The heat pump heated an 80 gallon buffer tank of water to a temperature determined by the outdoor set point thermometer. The buried loop on the GHE side of the heat pump was charged with a 20% methanol, 80% water mixture. The loop on the building hydronic side of the heat pump was charged with water. The data acquisition system consisted of BTU meters, ground loop (temperature) sensors, and current transformers and power meters for the circulation pumps. The temperatures within the soil were monitored across the differing surface treatments. The temperature of each loop as it returns to the building was also monitored. The heat pump system had a full monitoring system recording temperatures throughout the system as well as flows and electrical usage. Data was collected by data loggers and transmitted to a data network maintained by CCHRC staff.

Initial study operation began in October 2013 in order to document the long term effects of heat extraction on the ground thermal regime and any associated degradation in the efficiency of the heat pump system. Final construction and commissioning of the GSHP system were completed in November 2013.

Project Costs: The amounts of funding to accomplish this project came from three sources of funds: State of Alaska - $64,512, Denali Commission - $54,955 and Grantee cash match - $24,311. All funding was expended by the end of the grant funded activities. (NOTE: Amounts shown are subject to final audit by AEA.)

3 Sources Found

	Funding Source	Amount
	Total Denali Commission Funding:	**$50,385.42**
	Cold Climate Housing Research	$19,499.05
	State of Alaska	$59,147.73
	Total Other Funding:	**$78,646.78**
	Total Project Funding:	**$129,032.20**

Project Outcomes: The heat pump system replaced a 76,000 BTU/hr oil fired condensing boiler as the main source of heat for this portion of the building.

Problems Encountered: The following challenges were experienced in the execution of this grant:

- In the initial installation the current transformers (CT) monitoring the circ pumps were found to be incompatible with the power meters. The CTs were later replaced with compatible units.
- The continuous data from the Badger flow meters were not recorded on the data loggers due to a programming problem; however, pulse data from the flow meters was recorded which served the purpose.
- The heat pump went off-line in November 2013. In troubleshooting this problem, it was discovered that a fuse had blown on the control card and the compressor contactor had burned out. Both were replaced under warranty within two days of the event. Later in February 2016 a contactor was replaced under warranty as well.
- A couple of the ground temperature thermistors strings failed after installation. However, there was sufficient redundancy with data collected from other installed thermistors.
- Despite these few incidents, the demonstration system has generally been running well with minimal maintenance requirements since its installation.

Conclusions and Recommendations:

The primary questions which were to be answered by this study included the following: Does heat extraction in the winter create more permafrost? Or can the ground recover enough heat in the summer sun?

Previous GSHP studies in cold climates that analyzed heat production and efficiency found GSHP's work in cold climates in the short term. Coefficients of Performance (COP) during the heating season can range from 2 to 3.89 over the first two years of operation. But what happens to the efficiency over a longer term? Studies of cold weather GSHP installations question the long term effect of the thermal balance in the ground loop heat exchanger. The heat extracted from the soil during the heating season is generally greater than the heat rejected during the cooling season in colder climates. Soil temperatures can decrease over time, which leads to a decrease in GSHP performance. Depression of the soil temperatures around the ground loop is anticipated and can be acceptable if within design specifications.

The report discusses:

A. The cost and maintenance of the GSHP
B. The efficiency of the demonstration GHSP
C. The effects of various ground surface treatments on soil temperature
D. The results of the Life Cycle Assessment
E. The model used to determine the optimum depth of the GHE, and
F. The modeled long term efficiency of the GSHP.

A. **Cost/Maintenance of the GSHP:** The results of the operation of the GSHP system were that the savings in operating the GSHP over what the heating needs for the building using conventional stove oil in a 96% efficient boiler were highly dependent on the price of the stove oil. For heating seasons 1 and 2 (price of stove oil = $4.00/gal), the computed savings were $604 and $639 respectively, while in heating seasons 3 and 4 (oil price @ $2.35/gal), operating the GSHP system cost $207 more and $328 more (respectively) than the cost of using oil heat. So, even at $4.00/gal oil, the break even payback period for the total installed system cost (w/o monitoring and reports, $91,200) would be 147 years.
B. **Efficiency of the GSHP:** The efficiency of the heat pump varied over the course of each heating season. It tended to be higher in the fall when the GHE was the warmest and decrease over the course of the winter. However, as the heating demand of the building lessened the COP improved as the heat pump delivered lower temperature heat to the building. The annual COP and (associated electric cost) of the heat pump and the circulation pumps for the 4 years of operation was 3.69 ($890), 3.34 ($1,445), 3.01 ($1,666) and 2.82 ($2,360). The annual COP declined 24% over this 4 year period.
C. **Effects of Surface Treatments on Soil Temperature:** The ground's ability to reabsorb heat during summertime was tested by the spreading of three different materials over the loop field – dark rocks, sand and grass – to see how different landscaping affects the ground's ability to reheat. The temperature sensors in the manifold were set up to determine if the surface treatments were having any effect on the GHE. It was found that the fluid returning from the gravel loops is always slightly warmer than the other two surface treatment loops. The differences in the surface treatments are noticeable in the fall of 2015, with the gravel 0.5°C (1°F) warmer than the sand loops and 1°C (1.8°F) warmer than the grass loops. As the winter progressed the gravel loops stayed warmer than the other loops but there was not as much of a difference. The sand loops ended the winter season with the coldest temperatures. According to the manufacturer's information on this heat pump model a 0.6C° (1F°) change in the incoming temperature for the heat pump creates a 0.044 change in the COP of the heat pump. The 1C° (1.8F°) increase in the temperatures coming back from the ground loop could improve the COP only minimally (by 0.08).
D. **Life Cycle Assessment (LCA):** The LCA was conducted for the CCHRC GSHP in February 2014. The goal of the LCA was to understand the human health and environmental impacts of the installation and operation of a GSHP system in the RTF relative to other common heating system options. The LCA impact assessments illustrated below are separated into four categories: impacts to human health, ecosystem quality, natural resources, and climate change. The LCA found the GSHP to be roughly equivalent to traditional oil and gas boilers in terms of human health and environmental impact, this makes the decision to install a GSHP mostly economic. Considering the findings from both impact assessment methods, it appears that there are not

large differences in the overall potential impacts between the GSHP and combustion fuel heating scenarios for the CCHRC RTF. The GSHP scenario has slightly-to-significantly greater human health impacts relative to the combustion heating appliance scenarios, and slightly lesser natural resource impacts. There are no appreciable differences in the categories of climate change or ecosystem quality impacts. Therefore the motivations to choose a GSHP for this scenario appear to be primarily economic in nature, or originating from other preferences such as removing the need for on-site fuel storage.

E. **Modeling Optimum Depth of the GHE:** A numerical finite-element model of the ground in and around the GHE was developed to analyze questions that cannot easily or cost effectively be answered with the demonstration project. The model was constructed to simulate the heat transfer and phase change behavior of the ground surrounding the GSHP. This analysis allowed CCHRC to look at the performance of the system in the long term. It also evaluated the optimum depth for a ground coil at varying energy draws from the GHE. The numerical model helped to determine the optimum depth for a GHE in this application. It found there are diminishing increases in efficiency for installations deeper than 2.5 m (8 ft). In order to inform the design of the ground heat exchanger loop for the heat pump, a 2-D finite element model of the ground and ground loops was prepared. Following the design of the system a more refined 3-D simulation was created to look at the long term effects of the varying landscape choices on the heat recovery of the ground loop. The simulation shows the development of permafrost below the loop field within four years. Determining the optimal depth for future GSHP installations in the Fairbanks area should be assessed via finite element modeling.

F. **Modeling Long Term Efficiency of the GSHP:** The COP for the heat pump has trended lower over time, though the rate of decrease has slowed in year 4. Temperatures recorded in and around the GHE show cooling of the ground over the four years the heat pump has been in use when compared to the baseline data. The temperature at the depth of the coils shows 0°C (32°F) most of the winter, while the baseline temperatures are 3 to 4°C (5.4°F to 7.2°F) higher. At its coldest, the soil temperature has dropped slightly below 0°C (32°F) as the energy of phase change is extracted from the surrounding soils, freezing the soils before the temperature drops further. To date, the soil around the loops has risen above freezing each summer. The temperatures at 9’ depth (assumed to be the center of the GHE pipe coils) have remained close to the freezing line since December 2015. The modeling predicts the decline in soil temperature at the loop will level out around year 5. Permafrost tubes in the GHE show some frozen sections of soil within the area of the slinky coil in the center of the GHE. The frozen ground is not evident above or below the slinky coil zone, as far as can be determined from the permafrost tubes. To date, the ice around the slinky coils has not lasted the full year but permafrost is expected to develop in the next few years based on modelling. There was no ice below the active layer in any other locations or in any previous year. The grantee plans to continue to monitor the system's performance and effect on ground temperatures to determine if and when those metrics stabilize. The cost effectiveness of the GSHP depends upon the cost of oil vs electricity. At the current relative pricing the GSHP has cost more than a conventional high efficiency oil-fired boiler to operate over the 2015-16 and 2016-17 heating seasons. However, oil prices are expected to stay low.